Directed High Power RF Energy: *Foundation of Next Generation Air Force Weapons*

HPC Users Group Conference 2001
Biloxi, Mississippi
21 June 2001

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The Rocky Path to Fruitful HPM Simulations

- **The importance of *simulation* has been well known to many scientific and technological communities.**
  - **NASA, nuclear laboratories, etc.**
- **Simulation in HPM has not been forth-coming.**
  - **The first fully simulation-based design of a new HPM source was tested only recently.**
- **Partly due to experimentalists' lack of trust in HPM simulations because of:**
  - **Inadequate resolution attainable to discern relevant physics.**
  - **Inability to model a system in its entirety.**
- **Partly due to excessively long "real" simulation time possible on older hardware.**

The Rocky Path to Fruitful HPM Simulations (Continued)

- **The inability was not due to lack of proper Physics in codes.**
  - **PIC Physics still basically the same as coded into the early codes by the pioneers in the field.**
  - **Lacking was proper code architecture, effective hardware speed and data handling capacities.**
- **The landscape has changed with the advent of DoD's massively *parallel* computer clusters and the parallel PIC codes.**
- **Now we can glance into our RF sources with *quantum eyes*, the process slowed down a billion times, and see how the RF is generated.**

The Evolution of Computational HPM

Electromagnetic Codes Only

- **1-D PIC (non-rel)** — **Concept Validation**
  - **60s – 70s** — **Also possible analytically**

- **2-D PIC (non-rel)** — **Qualitative Description**
  - **70s** — **Limited predictive power**

- **2.5-D PIC (rel)** — **Diagnostics, Comp. Desg.**
  - **70s – 80s** — **Design possible, not practical**

- **3-D (rel., parallel)** — **Quantitative Dscrpt., Design**
  - **90s** — **System modeling possible**

The Evolution of Computational HPM
(Things To Come)

- **3-D (rel., parallel)** **Modeling of High Frequency Extended-Body Sources**
- **3-D (rel., parallel)** **Interactive Optimization**
- **Quantum Computing ?** **Real-Time Simulation**
  - **1 qubit potentially holds many pieces of information**
  - **n qubits of N states each, hold N^n pieces of information**
  - **When an operation is carried out on one state, the operation is simultaneously carried out on all states, a speedup of N^n. A computer with 50 qubits of 2 states each is 10^{14} times faster than the conventional counterpart with the same no. of bits**
  - **New concept in parallel computing**

Outline of the Talk

- **Accomplishments so far**
  - **Concept validation, Design**
  - **Diagnostics**
  - **ICEPIC, *an example of modern PIC codes***
- **Near-future goals**
  - **higher resolution, speed**
  - **Dynamic Optimization, parameter search**
- **Far-reaching goals**
  - **More accurate Physics, non-linear dispersive media**
  - **Integration of non-EM and secondary EM effects**
  - **Real-time modeling and simulation**
  - **On-line holographic display of results**

AFRL COMPUTATIONAL PLASMA PHYSICS TEAM

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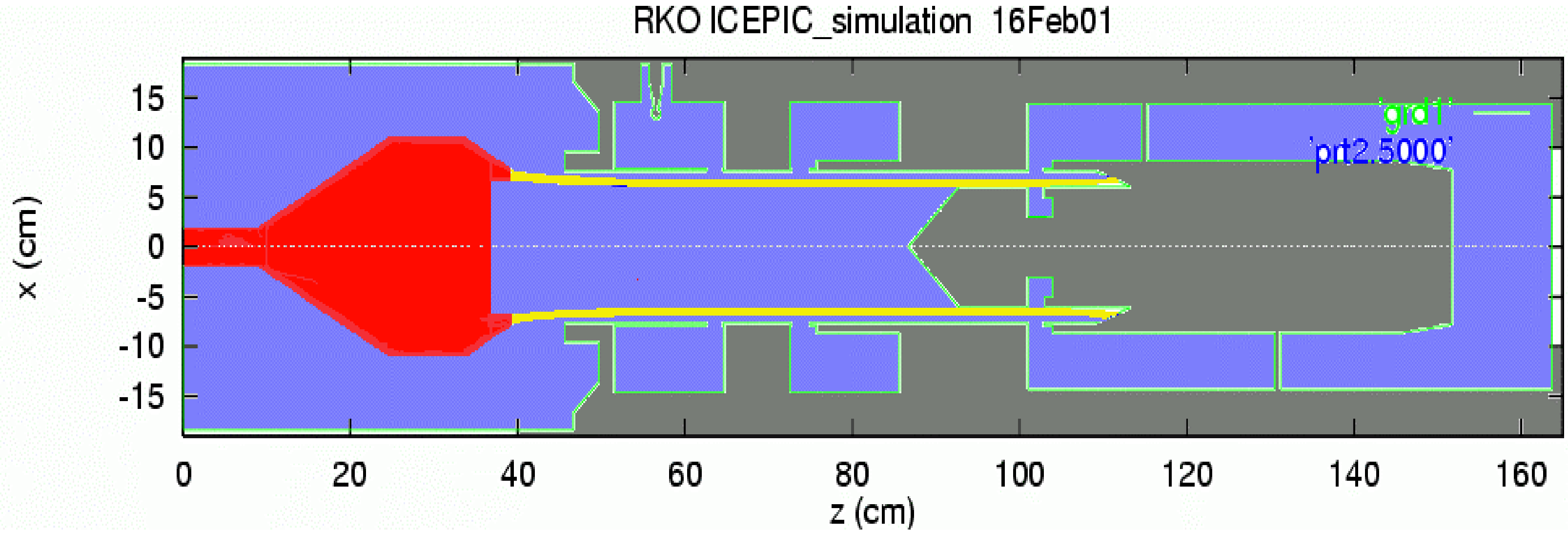
Snapshots in Time

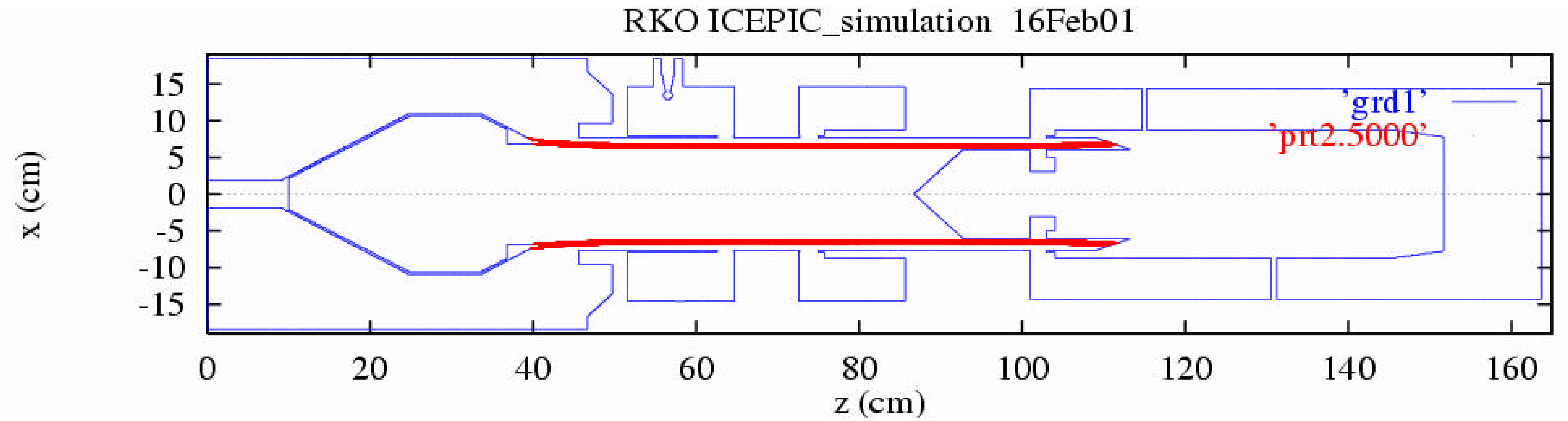
- In 1994, a state of the art calculation was a serial simulation of UNM's BWO:
  - Reduced simulation domain included only the interaction region (slow wave structure)
  - 35 cm x 2.5 cm
  - 40,000 cells (memory limited)
  - 5,000 particles
  - 24 hour run
  - *Qualitative insight*

- In 2000, a state of the art calculation was a parallel simulation of AFRL's MILO:
  - End-to-end simulation domain included extractor, antenna, and realistic pulsed power
  - 215 cm x 14 cm x 14 cm
  - 20,000,000 cells
  - 500,000 particles
  - 36 hour run on 120 processors
  - *Quantitative Prediction*

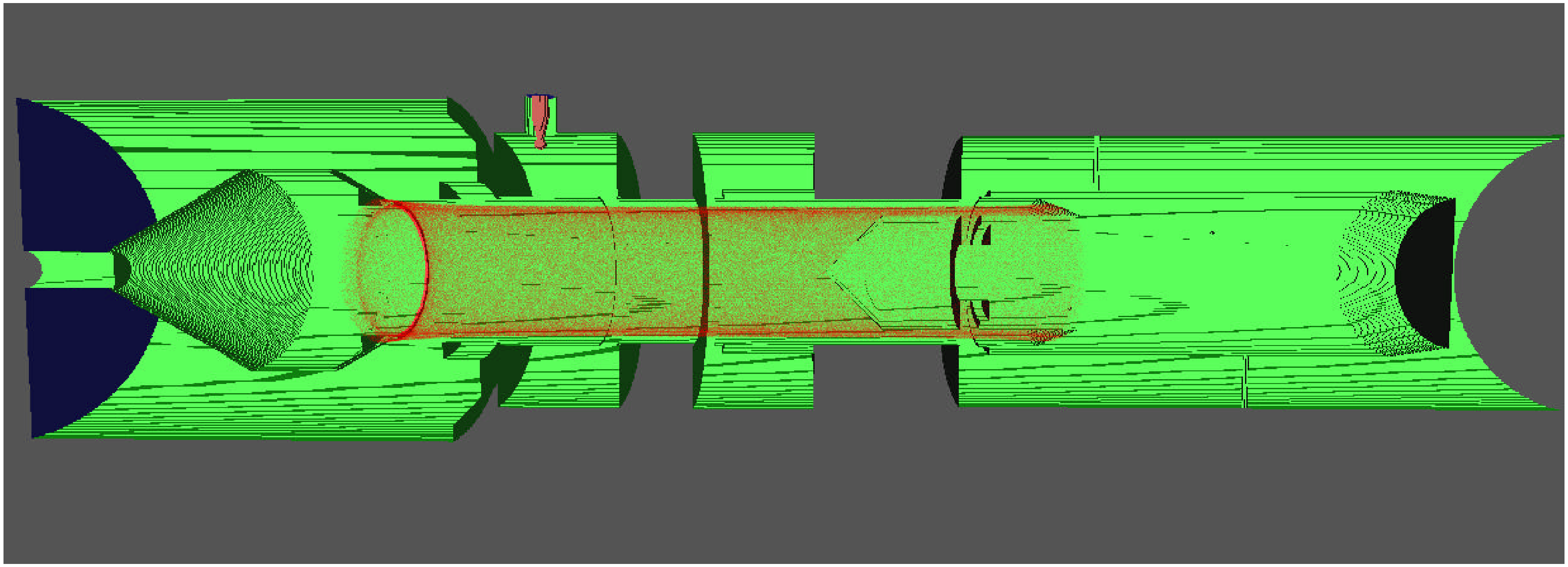
An Example of What is Possible

Axial section of the Relativistic Klystron Oscillator





CUT OF RKO



Cut-away view of the RKO shown with the beam and the RF feed in the 1st Cavity

The Challenge in mm-wave Devices

- **For resonant cavity sources, size scales with λ**
- **At small (mm) wavelengths and multi-MW devices, the device is too small to stand the heat.**
- **Gyrotron family of devices allow small wavelength at a reasonable device size;**

But at a price.

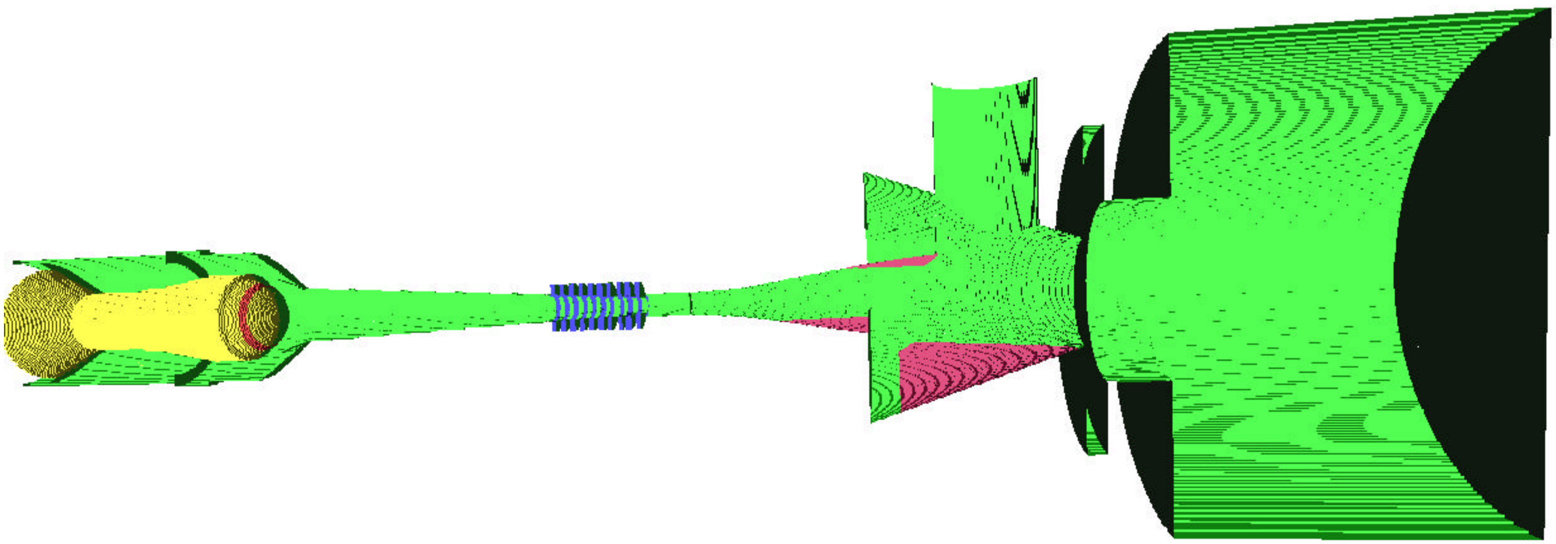
- **FDTD modeling becomes inhibitively expensive because of the need for resolving the wavelength.**
- **Let's see how**

How Close ?

- **For a mm-wave device at $\lambda=1$ mm, 1 m long and 0.25 m wide and uniform meshing, need 60 billion cells.**
- **At an average of 3 billion particles and 18μs/particle/processor with 64 processors on a typical machine, will take 15 min/time-step.**
- **For a 30 ns run, at dt=0.15 ps, will need 200,000 time-step, a total runtime of approximately 5 years per run.**
- **With the recently operational Machine Cobalt at ERDC, this runtime will be reduced to 2 months, possible but not practical.**

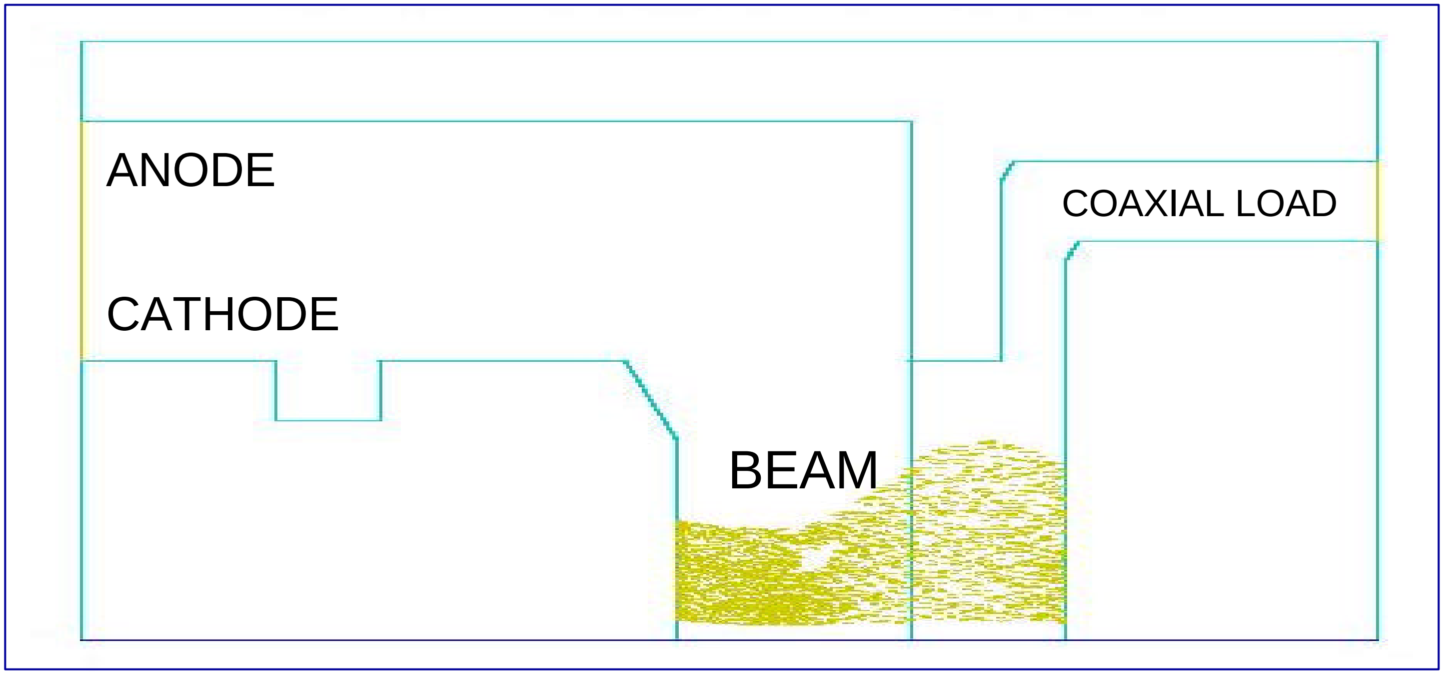
On The Verge of Being Possible

- **Gyrotron**



NEW HPM SOURCE

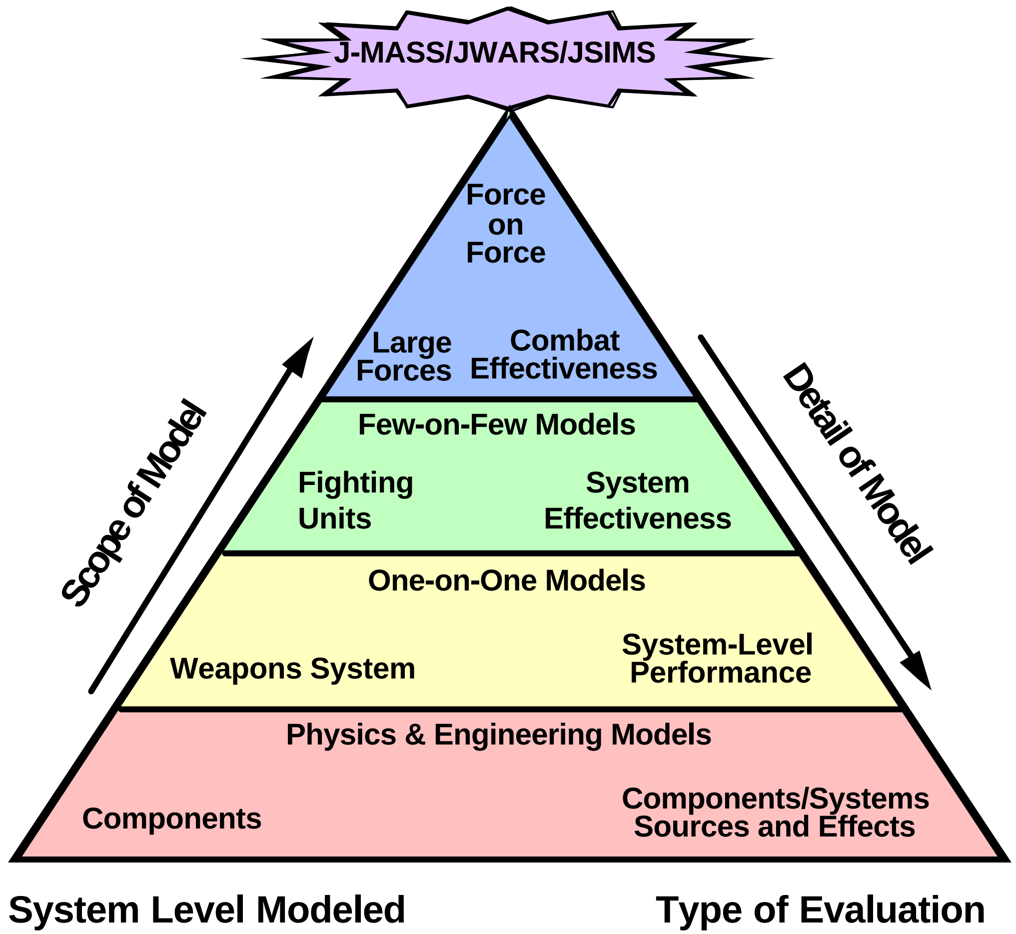
- **A new HPM device shown with the beam**



Next Generation Computers (and their makers)

- What we expect from the next generation of computers (quantum computers?) is the ability to model every system with higher resolution, more realistic Physics, and at a much higher speed.
- Near real-time simulation might enter the realm of possibility.
- Integration of non-EM effects, such as temperature, pressure, deployment related stresses on the system …, can become an issue.
- Integration of the HPM system with the deployment scenario in a real live situation might become possible.

RF Modeling Hierarchy



RF/HPM being incorporated into all levels of M&S

- **Force-on-force**
  - SUPPRESSOR
  - EADSIM (AF)
  - CASTFOREM (Army)
  - FEDS (Navy)
- **One-on-one / Few-on-few**
  - DREAM (DoD)
  - RF-ProTEC (AF)
  - SAPHIRE
- **Engineering**
  - CRIPTE
  - RFSPICE
  - HFSS
  - HEIMDAHL
- **Physics**
  - EM CODES
  - PIC CODES (ICEPIC)
  - MHD CODES (MACH)

RF Modeling Connections

AFOSR extramural HPC activities (Michigan, U C Berkeley, Washington)

DoD ASCI, etc. (SNL, LANL, LLNL)

OSD HPCMO

Center for Plasma Theory and Computation

NRL

AFRL/DE non-HPM pulsed power activities funded by LANL, DoE, NASA

AFOSR, AFRL/VA (Hypersonics)

AFOSR extramural and MURI HPM and PP research (MIT, Clarkson, MRC, Tech-X, Texas Tech, Texas A&M, UNM, Michigan

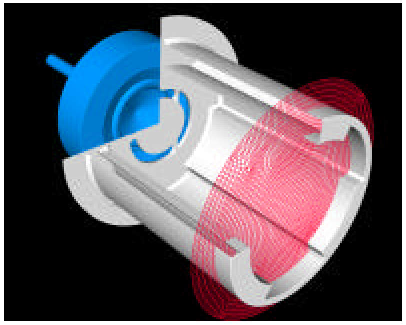
Analysis of Alternatives to Determine Best RF Source Modeling Software

- **2-D Electrostatic**
  - **ESTAT (Field Precision)**
  - **POISSON (LANL)**
- **2-D Gun (Steady fields, injected current)**
  - **E-GUN (SLAC)**
  - **TRAC (Field Precision)**
- **2-D Frequency-domain Electromagnetic**
  - **WaveSim (Field Precision)**
  - **Superfish (LANL)**
- **3-D Frequency-domain Electromagnetic**
  - **HFSS (HP)**
- **2-D Electromagnetic Particle-in-Cell (PIC)**
  - **MAGIC (MRC)**
  - **Two-QUICK (SNL)**
  - **X-OOPIC (UC Berkeley)**
- **3-D high-frequency E&M**
  - **X-Patch (SAIC)**
- **3-D Time-domain E&M**
  - **UPRCS (HyPerComp)**
  - **TSAR (LLNL)**

Adequate

- **3-D PIC**
  - **QUICKSILVER (SNL)**
  - **ISIS (LANL)**
  - **PIC3D (UK-Hockney and Eastwood)**
- **3-D packaged Electrostatic / Frequency-domain Electromagnetic PIC**
  - **ARGUS (SAIC)**

Sophisticated but Insufficient



***ISIS* image of Large Orbit Gyrotron (courtesy of Bon Kares, LANL)**

Plasma Physics and Numerical Simulation

Charged particles interact with applied and self-generated electromagnetic fields

Kinetic
- microscopic
- particle distribution is non-Maxwellian
- appropriate in low-density, low-collisionality limit
- possibly charged

↓

Particle codes

↓

HPM Sources, etc

Fluid
- macroscopic
- particle distribution is Maxwellian
- Appropriate in high-density, colisional limit
- charge neutral

↓

Magnetohydrodynamic codes

↓

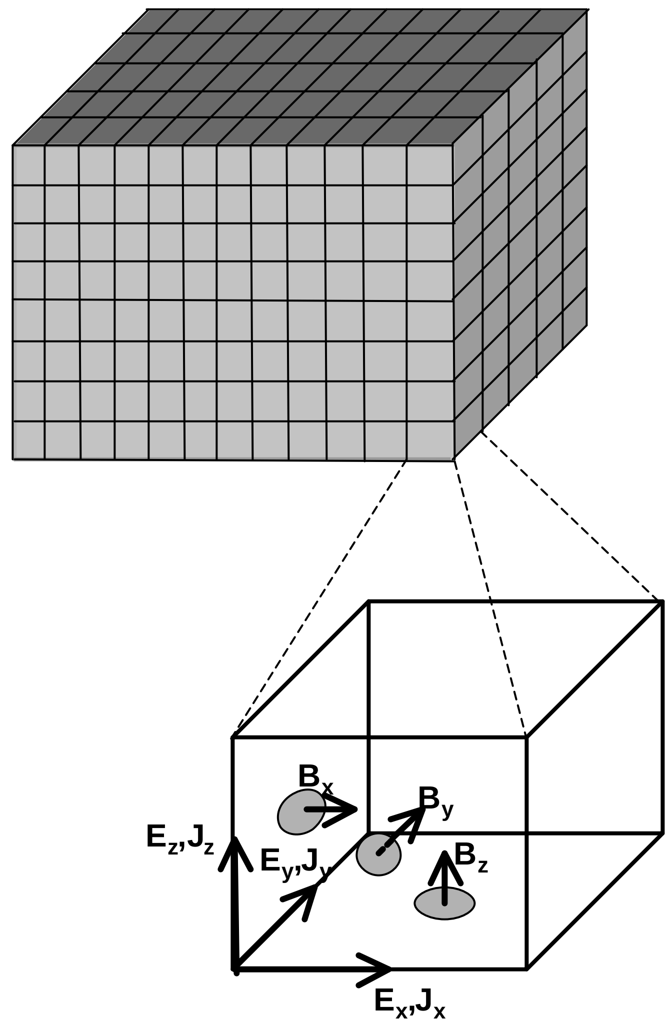
Plasma Aerodynamics, etc

How Does a FDTD PIC Code Work?

- **The problem volume is subdivided into millions of small cells; the cell size determined by the resolution sought. The evolution is worked out step by step, for a large number of time steps.**
- **For Each time step:**
  - **Fields are updated for each cell using the charge currents calculated in the previous time step.**
  - **Maxwell's equations are advanced for the electric fields by the time step, determined by the cell size.**
  - **Particles are moved by Lorentz forces for the time step.**
  - **Maxwell's equation are advanced for the magnetic fields.**
  - **Currents associated with the particles' move are calculated.**
- **New cycle begins.**

ICEPIC, *History*

- **ICEPIC was conceived in 1994**
  - **To be parallel (use multiple CPUs and memory)**
    - **Challenging because of PIC's dual data structure (particles and fields)**
- **Leverage priority access to DoD HPC Modernization Program computing assets to allow virtual prototyping capability**



ICEPIC, *Equations*

Maxwell's Dynamical Equations:

$$\nabla \times E = -(1/c)\partial B/\partial t$$

$$\nabla \times H = (4p/c)J + (1/c)\partial D/\partial t$$

Subject to the initial value constraints:

$$\nabla \cdot B = 0$$

$$\nabla \cdot D = 4pr$$

With the definitions for isotropic macroscopic media:

$$D = eE$$

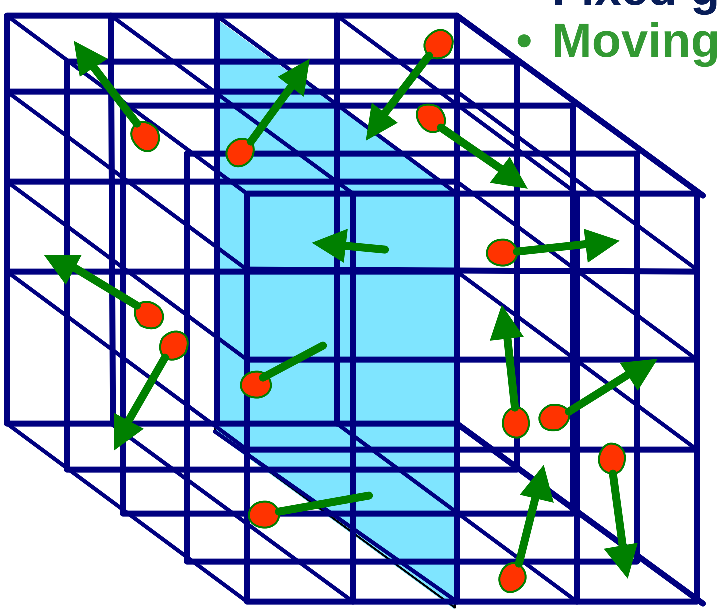
$$B = mH$$

Relativistic Lorentz Force Law for relativistic momentum *p* and velocity *u*:

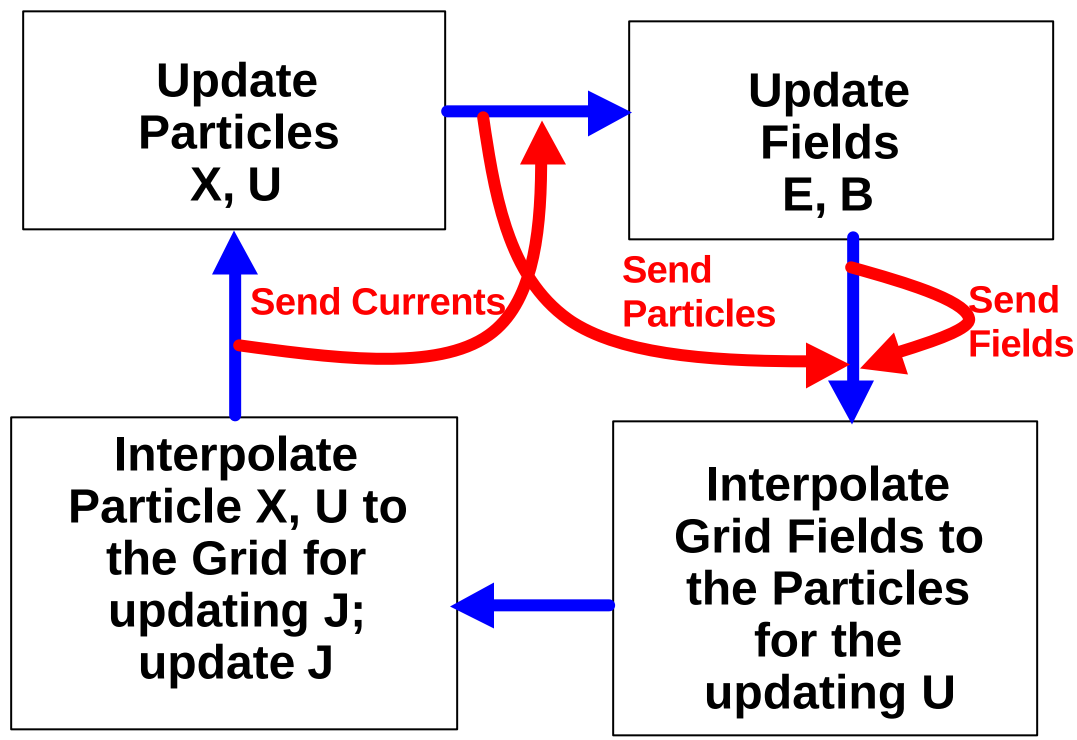
$$dp/dt = (q/c)\left[gcE + u \times B\right]$$

Particle-in-Cell has a dual data structure that makes efficient parallelization a challenge

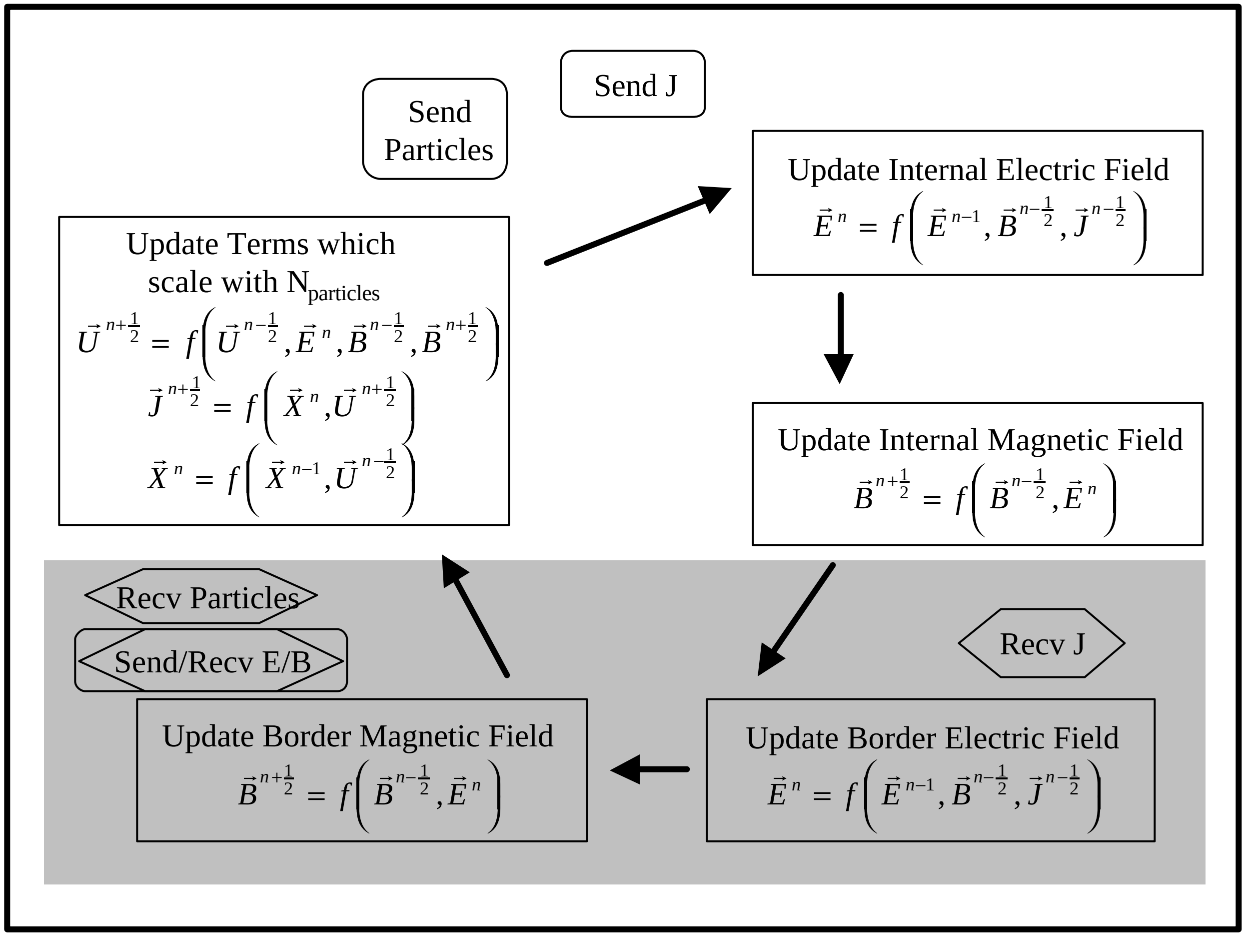
A challenge for load balancing via domain decomposition:
- Fixed grid supports the fields (E and B) and currents (J)
- Moving particles are the sources (X, U)



A challenge to hide communication with computation:
- PIC Data Flow for serial computing
- Sends and Receives for concurrent processing



New Parallel PIC Algorithm: Efficient Single Domain Decomposition



The PIC algorithm is modified by using:

- Asynchronous communication
- Combining electric and magnetic field messages
- Separation of border cell updates from internal updates
- All blocking receives now isolated (grey box)

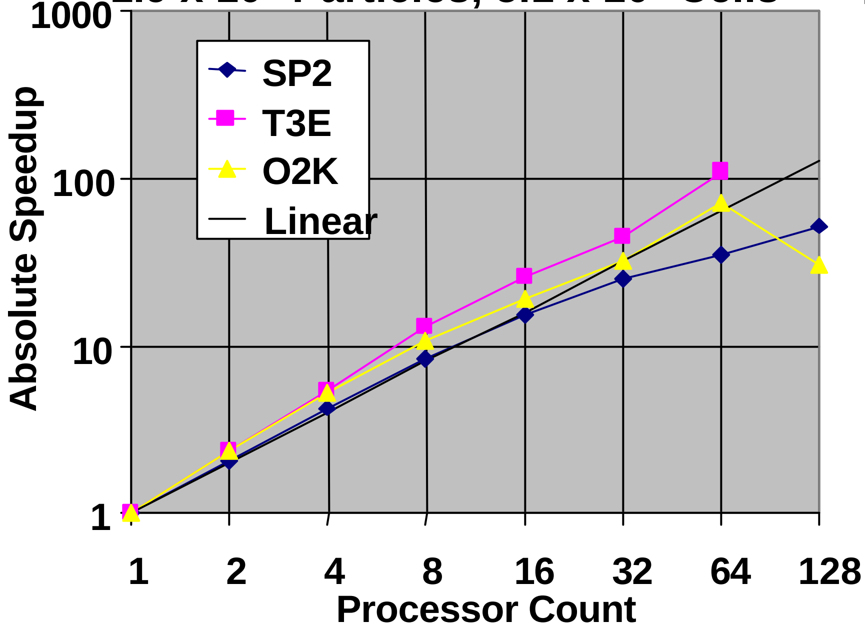
The simulations may now be partitioned and load balanced across all PEs

ICEPIC *is the First PIC Code to have* simulated Over One Billion Particles

- We have simulated as many at 2.2 *Billion* particles with *ICEPIC*
- Such heroic calculations require hundreds of PEs
  - Getting more that 128 PEs is challenging in a sharred computing environment
  - Getting fewer than 128 PEs is routine

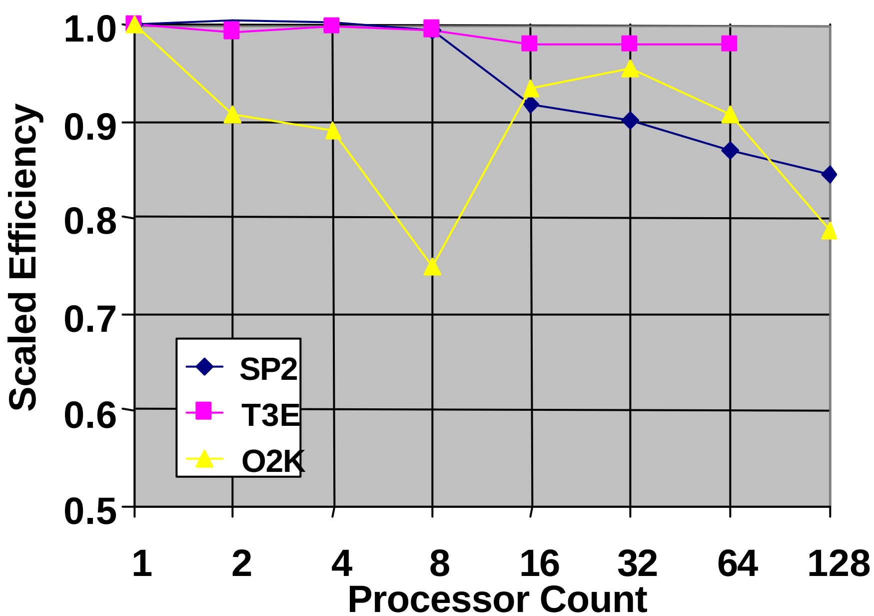
Fixed Problem Size

1.9×10^6 Particles, 5.1×10^4 Cells



Scaled Problem Size

1.3×10^6 Particles, 3.8×10^4 Cells *Per Processor*



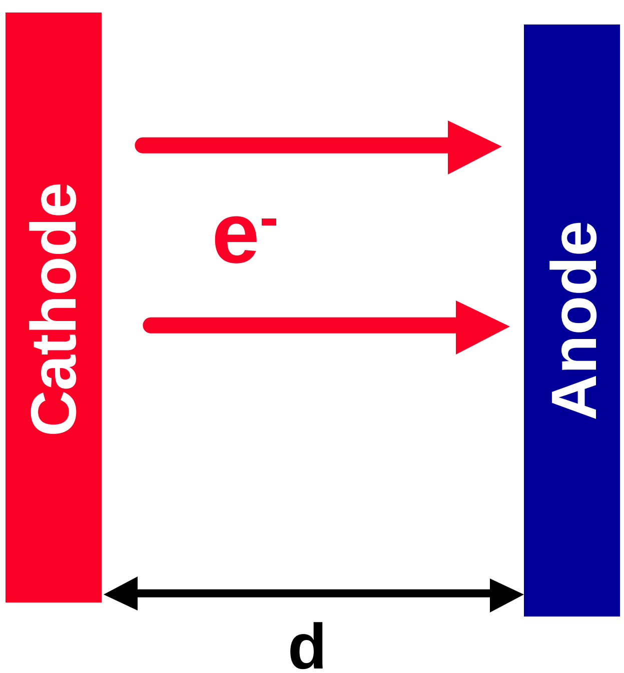
Space-charge limited Charged Particle Emission Algorithm

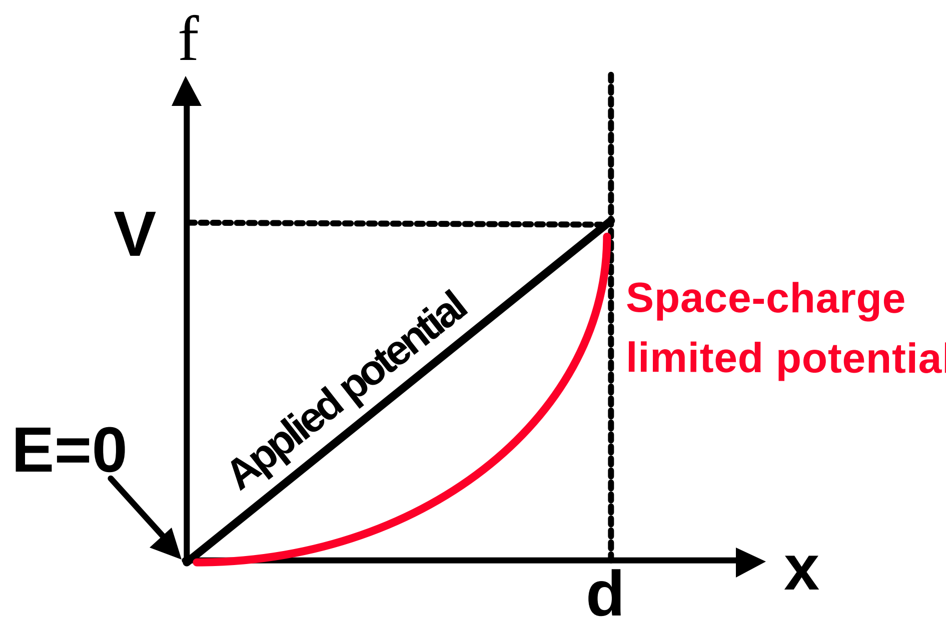
Background:

- **ICEPIC (Quicksilver, MAGIC) failed to compute the observed relation between applied voltage and extracted current in the RKO**
- **The computed current depended strongly on the mesh resolution**

Space-Charge Limited Emission:

- **An applied electric field draws enough charge from the cathode to cancel the normal component of the applied field**

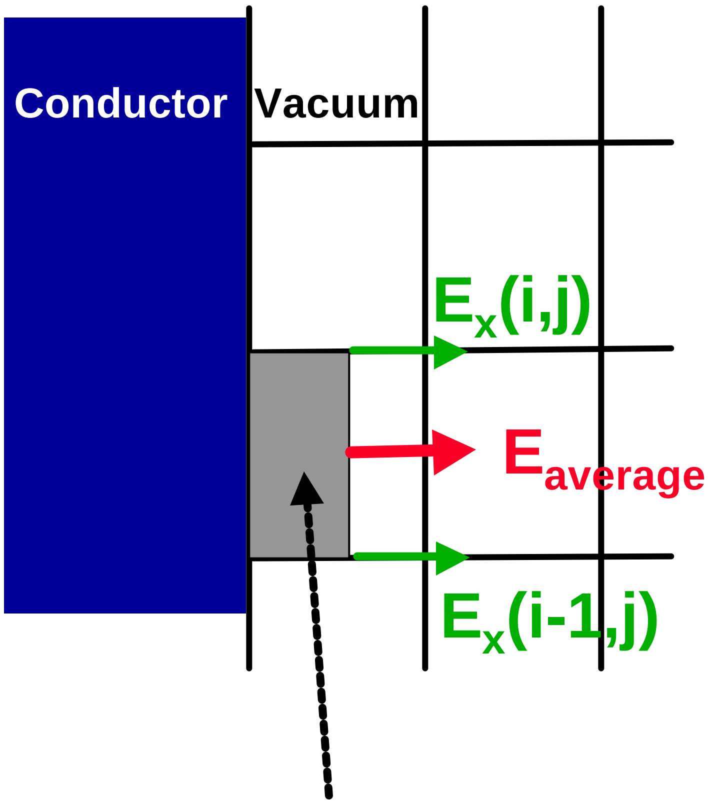




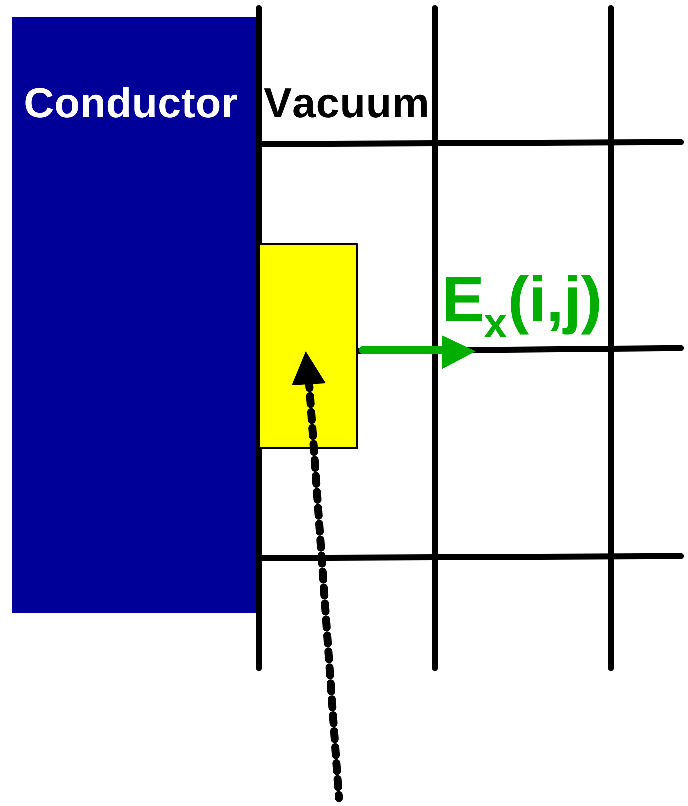
Computational SCL Emission: *Gauss' Law*

(Watrous et al., *Phys. Plasmas*, Jan 2001)

$$\nabla \bullet D = 4p r \Rightarrow \oiint_S D \bullet ds = 4pq$$



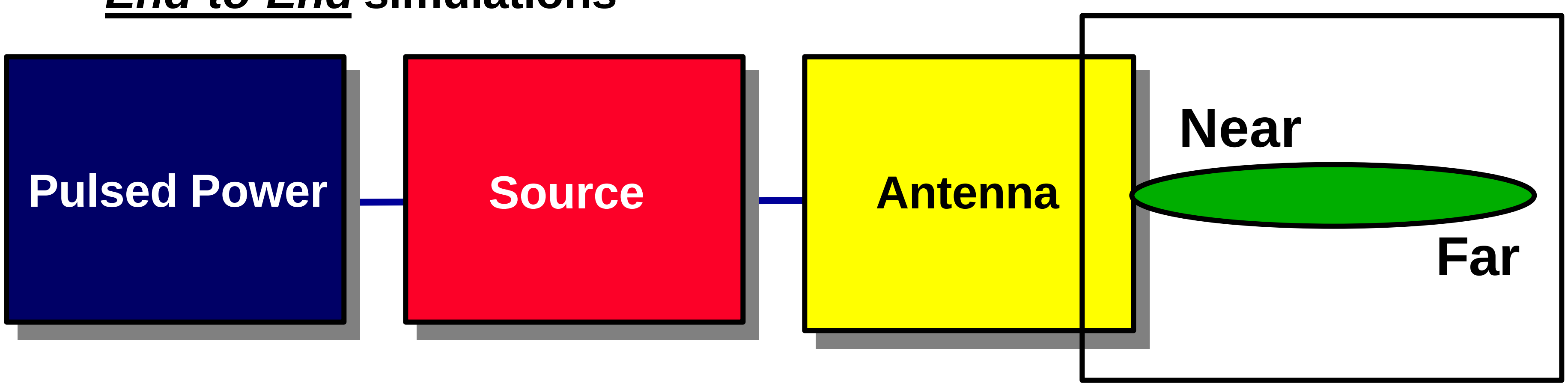
Primary Cell Integration Volume



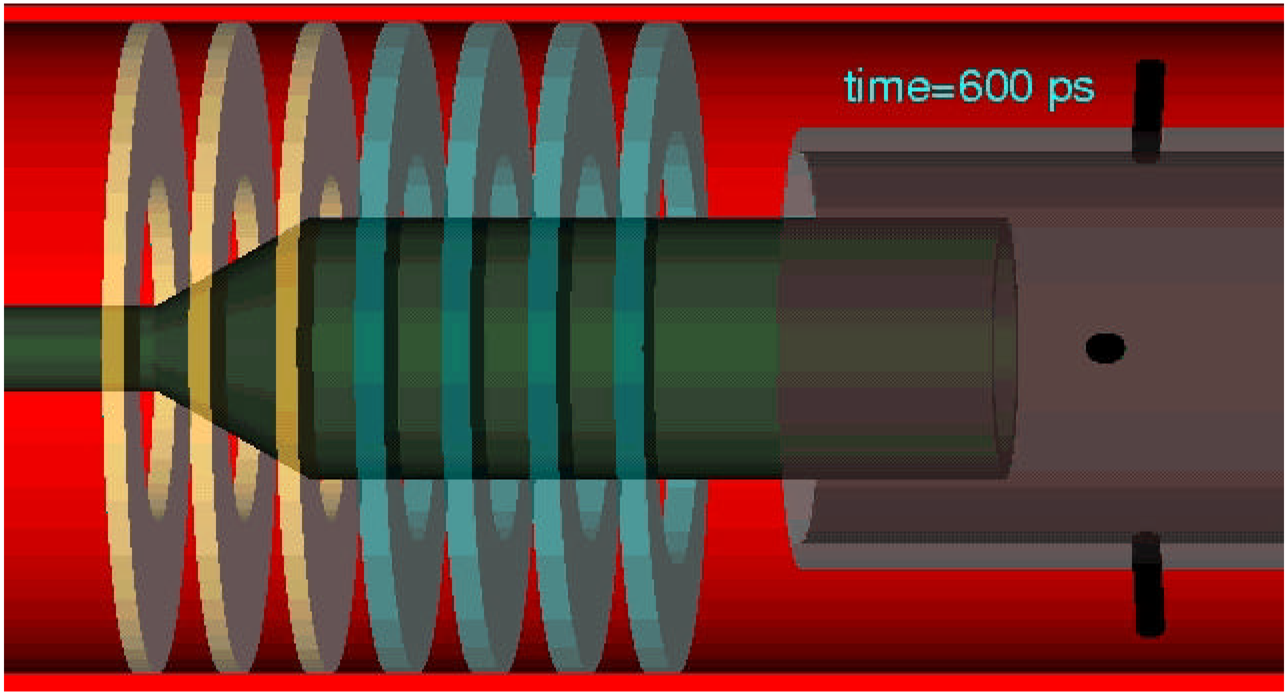
Dual Cell Integration Volume

Modeling Systems
Applications

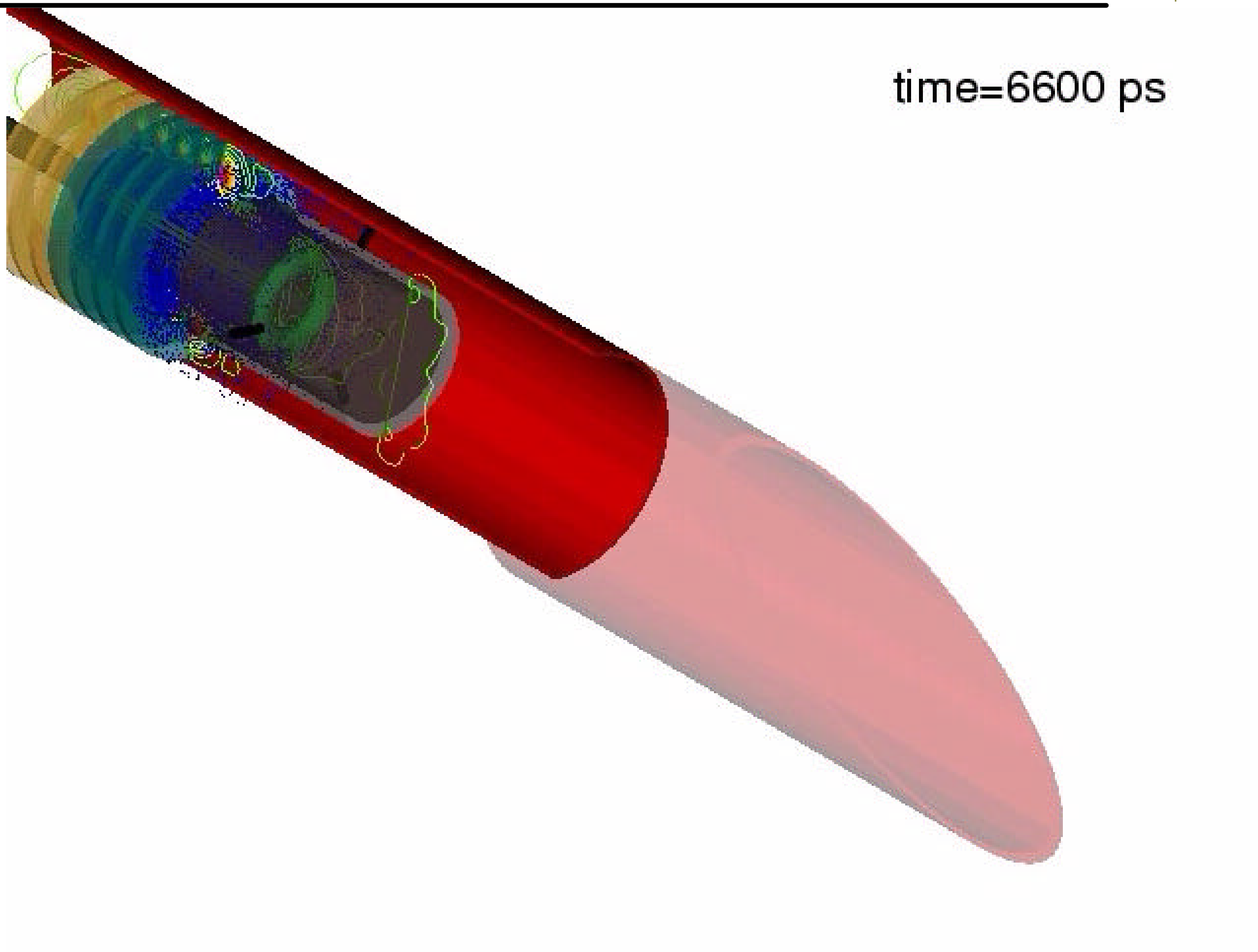
- Current philosophy of ***<u>Virtual Prototyping of RF Weapons</u>*** is to use different software to simulate different pieces of an HPM system
  - Components have different temporal and spatial scales
- This allows us to take advantage of the strengths of particular software while reducing the computational cost of a given, albeit truncated, simulation
- Hybrid software coupled with faster computer hardware and parallel technology will eventually offer the possibility of true ***<u>End-to-End</u>*** simulations

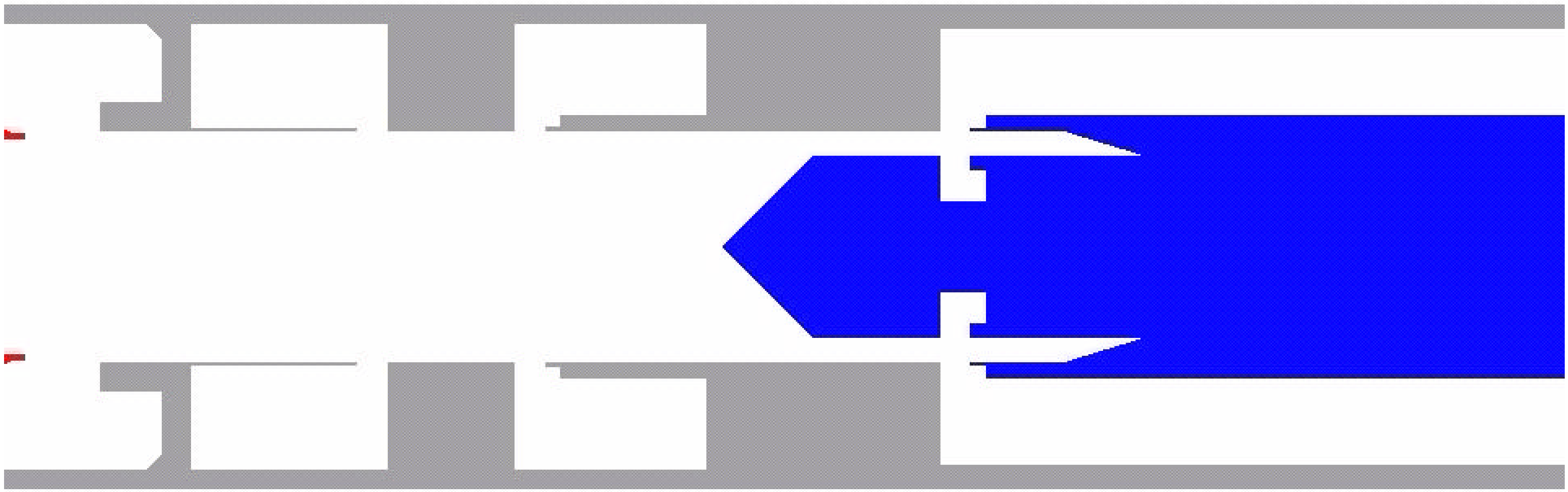


MILO MOVIE



MILO MOVIE



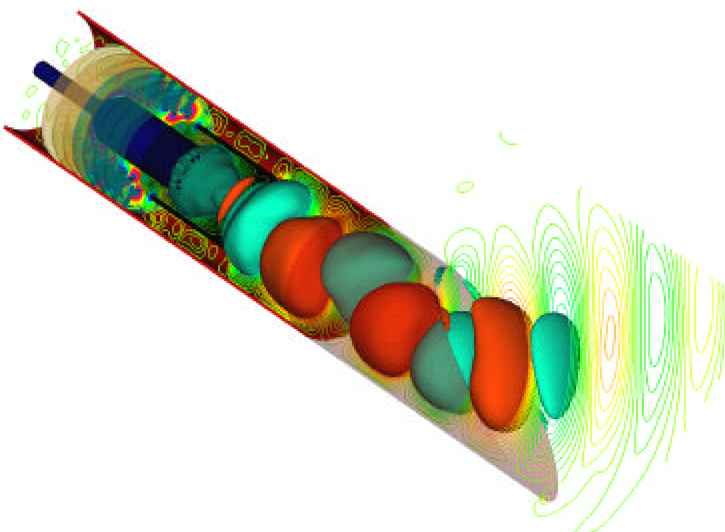


CONCLUSIONS

- **Analytical Approach to HPM problems intractable due to non-linear nature of interactions involved**
- **Numerical approach currently the only alternative**
- **Realistic and useful modeling of “some” HPM systems possible**
- **High frequency high power sources still difficult to model but within reach**
- **Integration of the HPM system with the deployment scenario in a real live situation might become possible.**
- **Quantum computing will bring next revolution**

RF Modeling Technology

Mission: **To develop and apply theory and advanced computation to enhance the development of HPM and related technology for the DoD.**



AFOSR HPC Star Team

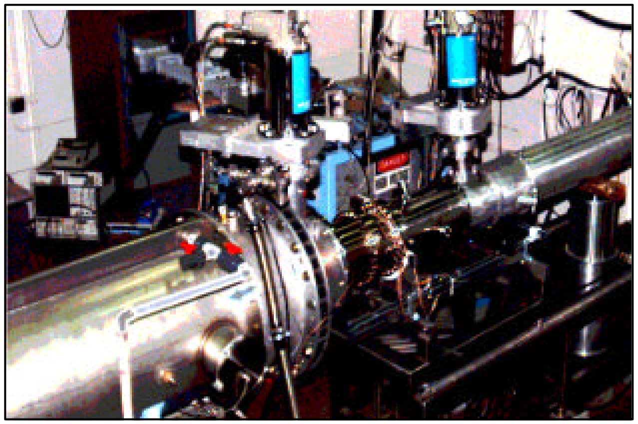
Approach: **We use the best software available to analyze existing and design future HPM components. When the proper software doesn't exist, we develop our own.**

Vision: **We perform *Virtual Prototyping* for Directed Energy concepts**

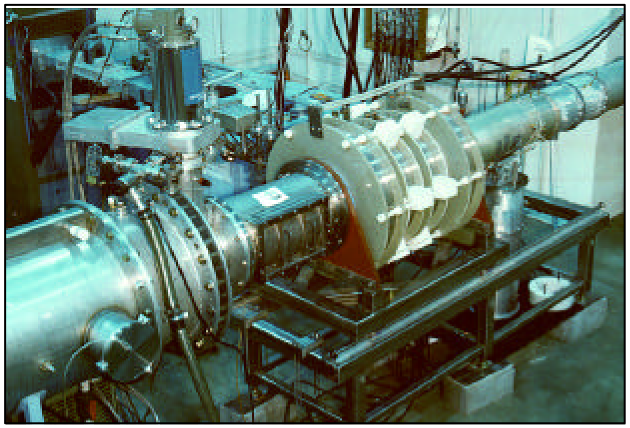
AFOSR HPM INITIATIVE STAR TEAM

Narrowband Sources and Associated Pulsed Power are Complex

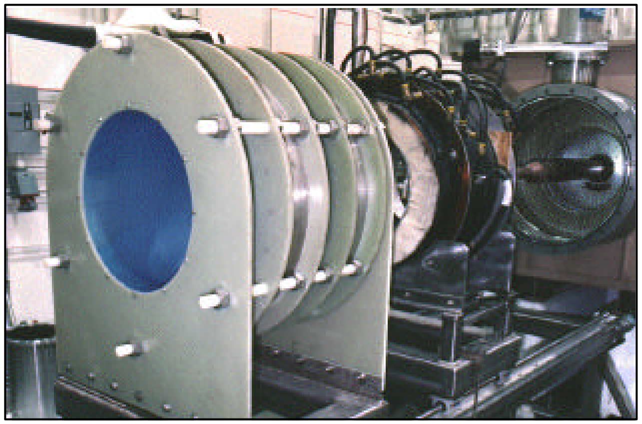
The physics of complex pulsed-power driven intense relativistic electron beam narrowband HPM sources are appropriately studied with the techniques of plasma physics



Magnetically Insulated Line Oscillator (MILO)



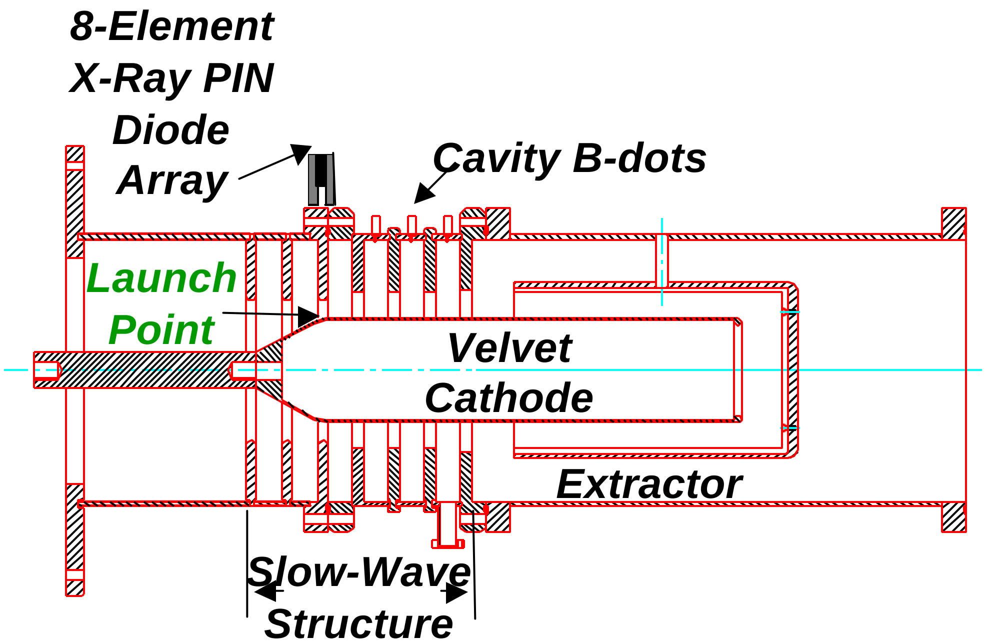
Relativistic Klystron Oscillator (RKO)

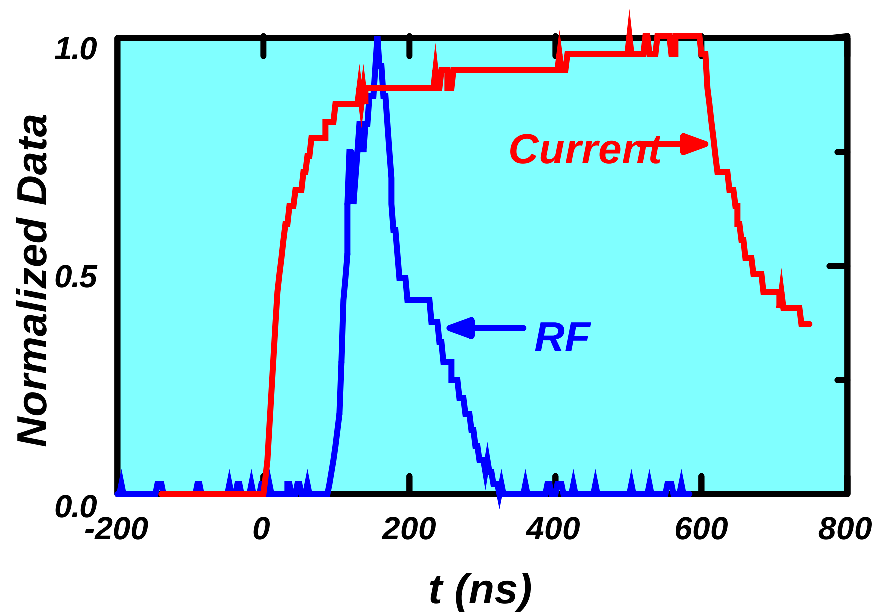


Gyro-BWO (High Power & Frequency Agile)

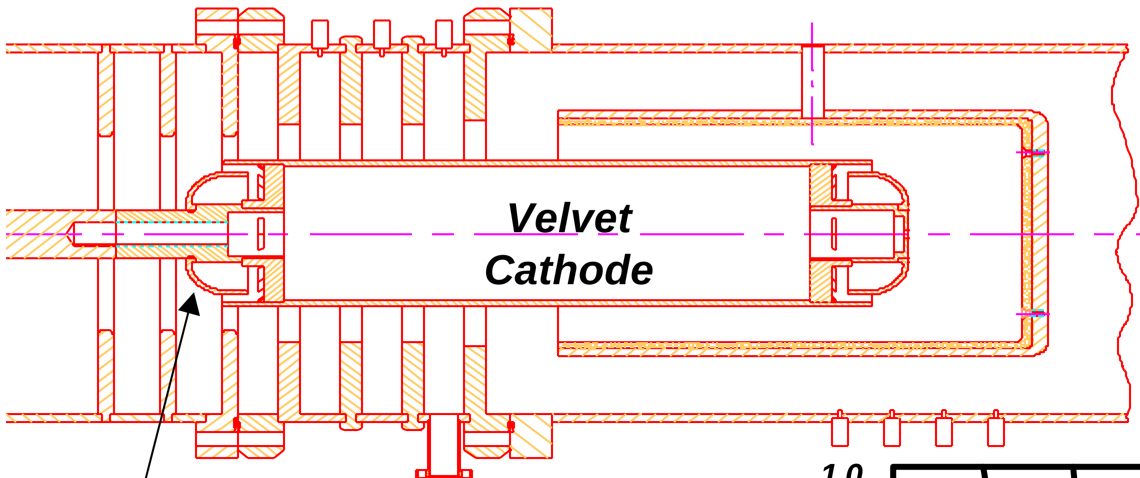
Impact of *ICEPIC* Simulations of MILO: the Problem

- Laboratory device exhibits unexpected RF pulse shortening
  - Current duration: 500 ns
  - RF duration: 200 ns



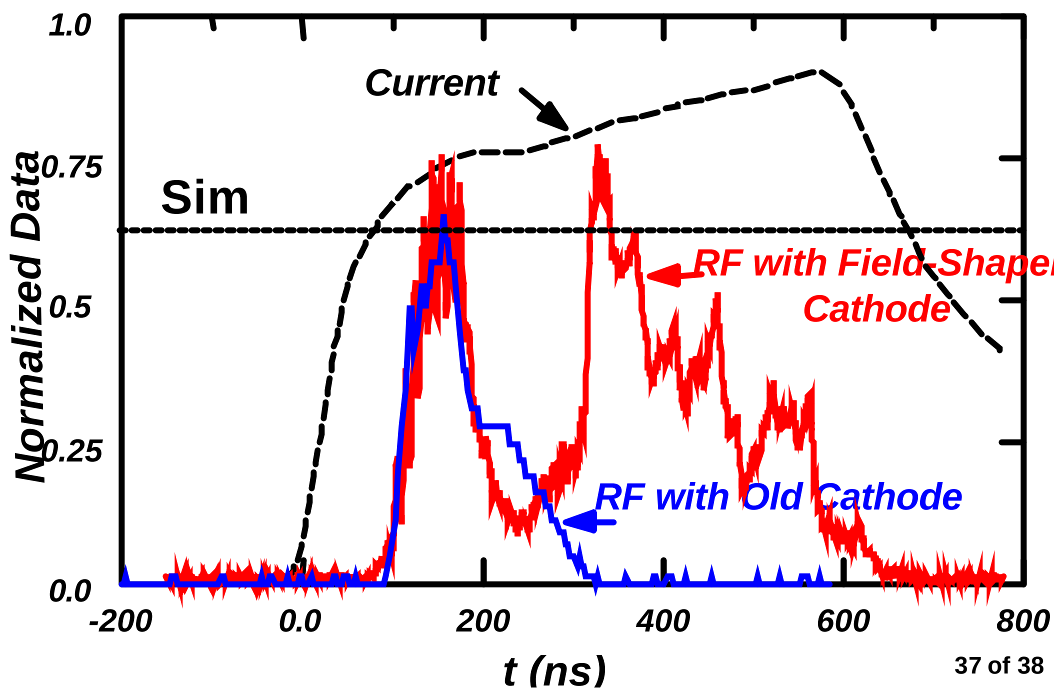


Impact of *ICEPIC* Simulations of MILO: The Solution, Continued



Modified Launch Point with field-shaper

- **Modified geometry has longer RF pulse**
- **Unexpected dip in power still not explained**
- **RF pulse has flat top (at reduced magnitude) when driving voltage is lowered from 500 kV to 300 kV**



AFOSR Lab Task in Computational Mathematics

This laboratory task addresses the need to enhance significantly the AF plasma and electron beam simulation ability:

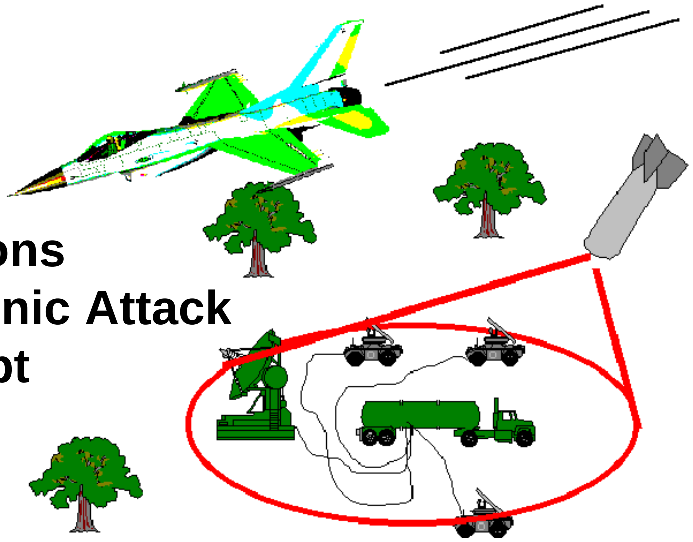
- **develop algorithms and data structures for accurate, efficient, scaleable parallel plasma simulation,**
- **develop a flexible, modular, portable, parallel, three-dimensional, relativistic, particle-in-cell simulation code for *unsteady* rare plasmas,**
- **develop a fully-capable, portable, parallel, three-dimensional, non-ideal *unsteady* magnetohydrodynamics simulation code for dense plasmas,**
- **develop time saving parallel programming software concepts of general use on current and future high performance parallel computers,**
- **incorporate into the simulation codes the scientific foundations necessary to capture all of the important plasma physics in three spatial dimensions, with special attention paid to the rare collisionless and dense collisional limits,**
- **incorporate into these codes parallel, adaptive 3D mesh generation methods for complex geometries,**
- **use fast 3D visualization and rendering techniques.**

RF Modeling Philosophy

- Use many different techniques to analyze each problem
- Work closely with experimentalists
- Develop theory and parametric models for enhanced understanding, optimization, and various fidelity models
- Validate models with every piece of data available (analytic solutions, experimental data, alternative computational results)
- Require agreement between the models, or explanation of all discrepancies
- Develop new theories and algorithms to enhance predictive capability

RF Weapons Computing Requirements circa 1995

Munitions Electronic Attack Concept



Program Requirements

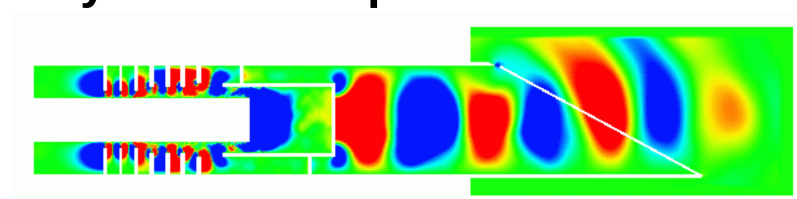
- Reduce the time and cost of RF weapons concept-to-batlefield via ***virtual prototyping***
- Predict effects of RF on targets
- Incorporate RF effects into M&S tools

Computational Requirements

- Need: End-to-end simulation
  - —Source components
  - —System integration
  - —coupling to target systems
- Near-term Requirement:
  - —Advanced algorithm development
  - —Thousand-fold increase in computing speed and memory

Status

- 3-D time-dependent physics simulation of portions of RF sources and pulsed power systems now possible



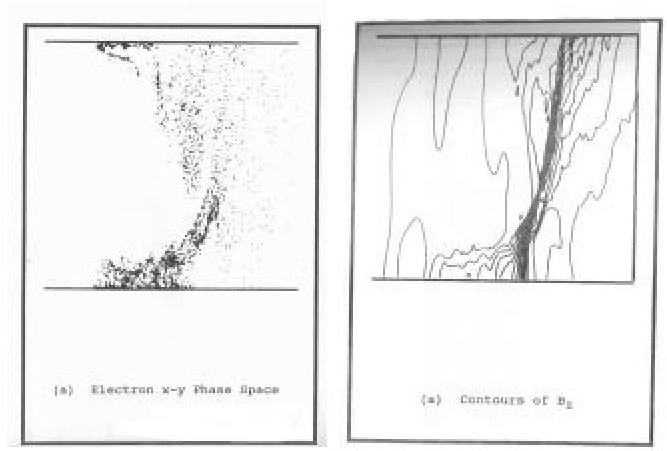
- Need new models for weapon-target interaction

RF Sources are Properly Modeled with Electromagnetic PIC Software

What is PIC?

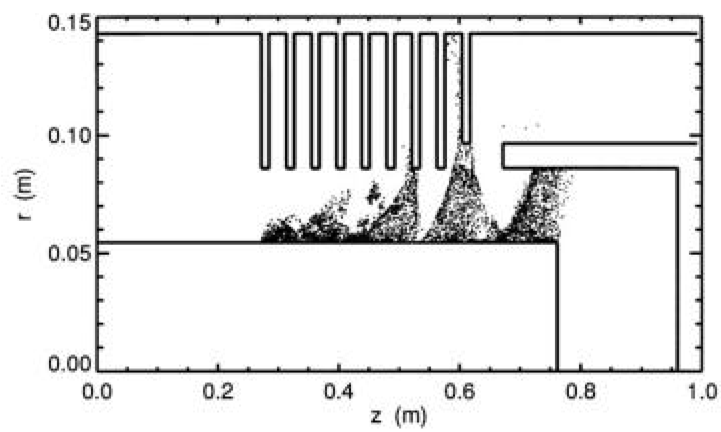
- **Models low-density, low-collisionality plasmas**
- **Fields represented on edges and faces of a fixed mesh**
- **Charged particles represented by macroparticpes in a continuous phase space**

15 years ago



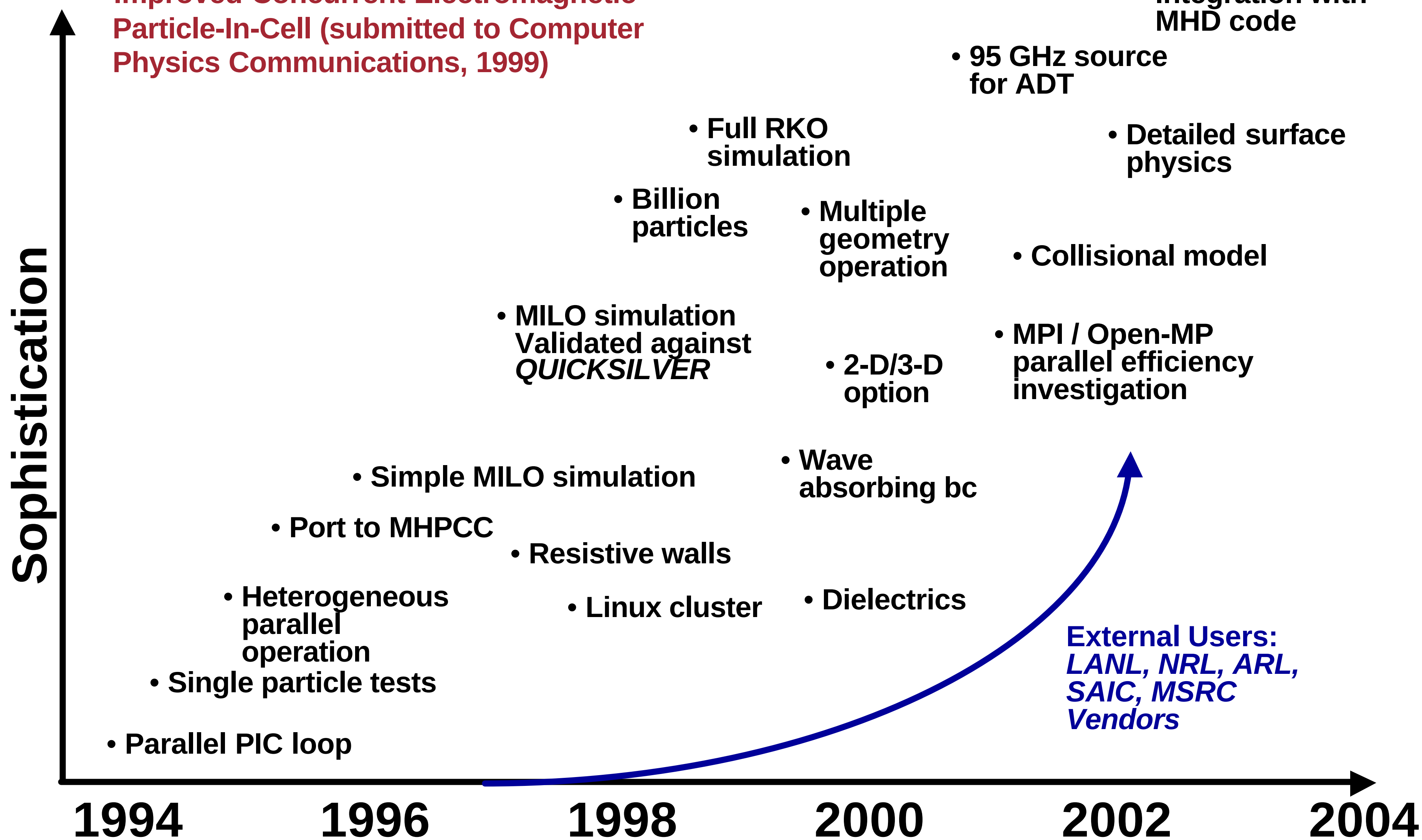
- **Limited 2-D PIC calculations performed with a hundred thousand particles in simple geometries to help to understand basic physics phenomena**
  - **e.g. 2-D *Magic* calculation of a Plasma Opening Switch from SAND88-7154, E. L. Lindman, Jr. and J. M. Kindel**

5 years ago



- **Advanced 2-D and and limited 3-D PIC calculations performed with a million particles to iterate with experiment to make incremental improvements to hardware design**
  - **e.g. 2-D TwoQuick calculation of a MILO by Ray Lemke.**

*ICEPIC** Development



* Improved Concurrent Electromagnetic Particle-In-Cell (submitted to Computer Physics Communications, 1999)